High dielectric insulation coating for time domain reflectometry soil moisture sensor

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[1] Insulation coating is often applied to time domain reflectometry (TDR) soil moisture sensors to reduce the conduction loss of energy. However, because of low dielectric constants of common plastic insulation materials, sensitivity is reduced, and the measurements are strongly dependent on coating thickness. Analytical studies clearly showed that these unwanted features could be mitigated if a high dielectric material is used for coating. An epoxy-ceramic nanocomposite was selected as a high dielectric insulation material because of its high dielectric constant and high adhesion. Experimental work using this composite indicated that the material has the potential to be used as a high dielectric coating for TDR soil moisture probes. On the basis of the results of these analytical and experimental studies a framework for designing an improved epoxy-ceramic composite for coating TDR soil moisture sensors is suggested. *INDEX TERMS:* 0684 Electromagnetics: Transient and time domain; 1866 Hydrology: Soil moisture; 0624 Electromagnetics: Guided waves; 0634 Electromagnetics: Measurement and standards; *KEYWORDS:* time domain reflectometry (TDR), soil moisture probe, water content measurement, dielectric constant, high dielectric insulation coating, epoxy-ceramic nanocomposite

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1. Introduction

[2] Time domain reflectometry (TDR) is a well-established method of measuring soil volumetric water content. Figure 1 shows a typical TDR waveform obtained from a TDR probe. The elapsed travel time between the partial reflection of the pulse from the beginning of the rod and the total reflection from the end of the rod can be measured from the waveform. For a probe of known length L, this travel time defines the average velocity of propagation along the probe, which is used to calculate the average dielectric constant over the rod length embedded in soil. The dielectric constant (K) is given by

$$K = \left(\frac{tc}{2L}\right)^2 = \left(\frac{c}{v_p}\right)^2 \quad (1)$$

where t is the time required for a voltage pulse to propagate a distance $2L$, c is the speed of light in free space ($= 3.0 \times 10^8$ m/s), and v_p is propagation velocity. The volumetric soil water content (θ) is calculated from the measured soil dielectric constant using a calibration curve empirically determined by *Topp et al.* [1980] as

$$\theta = -5.3 \times 10^{-2} + 2.92 \times 10^{-2}K - 5.5 \times 10^{-4}K^2 + 4.3 \times 10^{-6}K^{-3} \quad (2)$$

This equation has broad applicability to a wide range of soils.

[3] To determine the travel time t accurately, the total reflection from the end of the probe must be clearly seen in the waveform. As the pulse travels along the probe, it is dissipated through electrical conduction and dielectric relaxation, especially in soils with high clay content. In electrically conductive soils, excessive energy losses occur along the probe. This results in insufficient energy remaining to identify the reflection from the end of the probe. Therefore, to take measurements in conductive soils, rods can be coated with insulation coatings to minimize conductive losses. Frequency domain methods such as those described by *Jones and Or* [2001] have also been proposed for water content measurements in conductive soils. However, these methods are not discussed further in this paper. Insulation coatings that have been used for TDR probes include Teflon, PVC, epoxy and acrylic paint [*Baran*, 1994; *Kelly et al.*, 1995; *Benson and Bosscher*, 1999]. These materials are polymers that have low dielectric constants of $2 \sim 5$ at a frequency between 1 MHz and 100 MHz [*Lide*, 1995].

[4] However, these low dielectric insulation materials introduce the following disadvantages: (1) sensitivity of the TDR sensor is reduced and (2) measurements vary significantly with the insulation coating thickness. These disadvantages can be mitigated if the insulation material has a high dielectric constant similar to that of saturated soils, which is in the range of 30 to 40.

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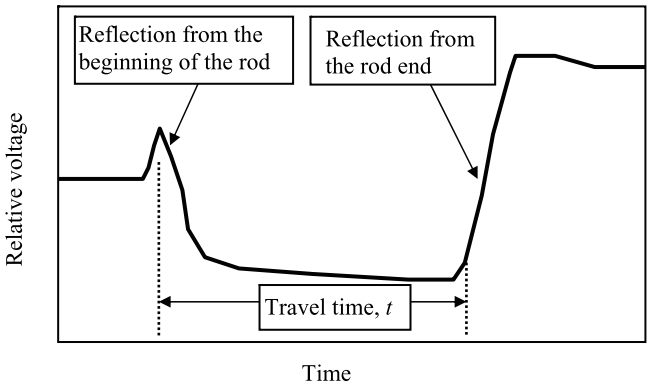

Figure 1. Typical waveform of probe inserted in soil.

[5] The objectives of this paper are (1) to give a theoretical explanation of the advantages of a high dielectric insulation when compared to a low dielectric insulation and (2) to introduce a polymer-ceramic nanocomposite as a potential high dielectric insulation for TDR sensors. Two-rod TDR probes will be used as an example for describing the concept of high dielectric insulation. Experimental work to evaluate the performance of the polymer-ceramic nanocomposite is also described.

2. Analytical Evaluation of High Dielectric Coating

[6] An apparent dielectric constant (K_{app}), which is directly measured using a coated probe, takes a value between the dielectric constants of the coating material (K_{coat}) and the soil (K_{soil}). According to *Annan* [1997], an approximate solution of K_{app} is given by

$$K_{app} = \frac{K_{coat}\cosh^{-1}\left(s_0/r_0\right)}{K_{soil}\left\{\cosh^{-1}\left(s_0/r_0\right) - \cosh^{-1}\left(s_1/r_1\right)\right\} + K_{coat}\cosh^{-1}\left(s_1/r_1\right)} K_{soil} \quad (3)$$

where s_0 is half of center-to-center spacing of rods, r_0 is the radius of rods, s_1 is half of center-to-center spacing of rods with coatings, and r_1 is the radius of rods with coatings. *Ferré et al.* [1996] used this analytical solution to examine the effect of air-filled gap, PVC coating (low-K coating) and water-filled gap (high-K coating) on soil water content measurements. The analytical procedure described below follows that of *Ferré et al.* [1996].

[7] Using this solution, the effects of K_{coat} and coating thickness (h) on K_{app} were evaluated. Keeping the rod radius to separation ratio constant ($r_0/2s_0$ = 0.08), the coating thickness was varied. A typical $r_0/2s_0$ value for two-rod probes is in the range of 0.05 to 0.10 [*O'Connor and Dowding*, 1999]. Two types of coating materials were assumed. One type is a common insulation material (e.g., PVC) with K = 3. The other is a material with K = 35, which is close to the high-end of K values exhibited by many soils and is considered to be an appropriate value to illustrate the advantages of a high dielectric insulation. Three different values were used for the dielectric constant of the soil (K_{soil}): values of 5, 20, and 35 corresponding to dry, moist but unsaturated, and saturated soils, respectively.

[8] A comparison of the calculation results is shown in Figure 2. The apparent dielectric constant (K_{app}) directly measured by a probe with high-K coating is similar to the actual soil K value. The results were almost identical when the K_{coat} value is varied in the range of 30 to 40. On the other hand, K_{app} measured by a probe with low-K coating can be significantly lower than the actual soil dielectric constant. This masking effect of low-K coating introduces two problems in determining soil water contents. They are (1) sensitivity of a TDR sensor is reduced and (2) apparent dielectric constants vary significantly with insulation thickness. These disadvantages can be mitigated using a probe with high-K coating because the apparent dielectric constant is theoretically very similar to the actual soil dielectric constant regardless of the coating thickness.

2.1. Sensitivity of TDR Sensor

[9] Suppose that there is an ideal soil whose dielectric constant and volumetric water content (θ) relationship exactly follows equation (2). Using equations (2) and (3), it is possible to calculate the apparent dielectric constant measured by a coated probe buried in the ideal soil having a specific θ. By repeating this calculation for different θ values, it is possible to obtain a curve that represents the relationship of K_{app} and θ for a coated probe buried in the ideal soil. Three types of coating materials of K_{coat} = 3, 35 and 100 with a uniform coating thickness of h/r_0 = 0.4 were assumed. This coating thickness ratio is within the range of 0.056 to 0.68 reported by different manufacturers of two-rod probes (IMKO and Soilmoisture Equipment Co.). The rod radius to separation ratio was also kept constant ($r_0/2s_0$ = 0.08).

[10] Figure 3 shows the calculated K_{app}-θ relationships for three coated probes and one uncoated probe. The curve for an uncoated probe is identical to equation (2). The "sensitivity" of a TDR probe can be defined as $dK_{app}/d\theta$

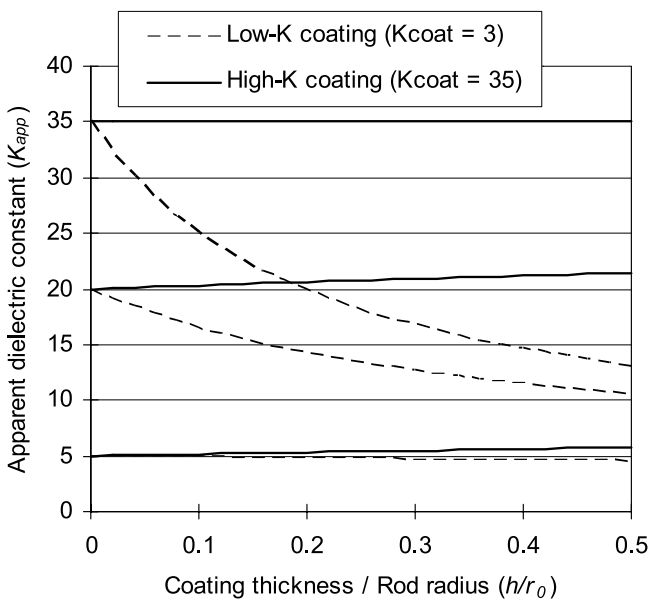

Figure 2. Effect of thickness of low and high dielectric coatings on apparent dielectric constants.

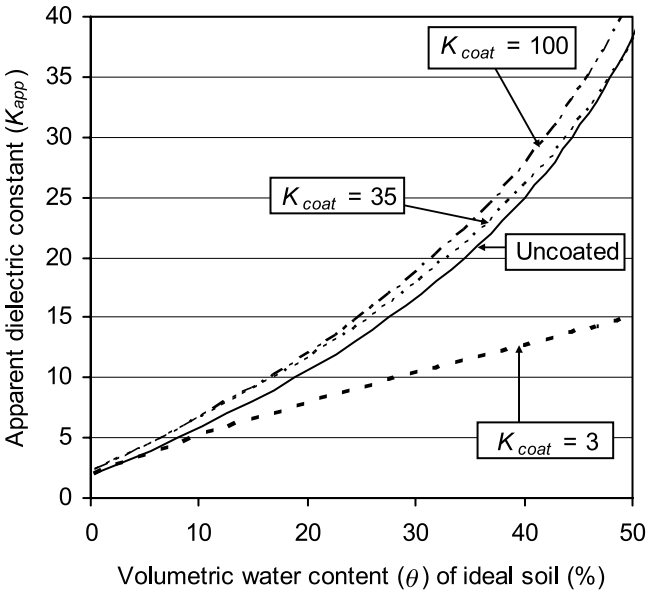

Figure 3. K_{app}-θ relationship for coated (h/r_0 = 0.4) and uncoated probes.

[*Ferré et al.*, 1996]. If the sensitivity is small, an error in the measured K_{app} will introduce a larger error in the calculated θ. As shown in Figure 3, the sensitivity of a probe with low-*K* coating is significantly smaller than that of an uncoated probe. This indicates that water contents determined using a low-*K* coated probe can have larger errors than those determined by an uncoated probe. The sensitivity becomes even smaller as the coating thickness increases. On the other hand, the K_{app}-θ relationships for high-*K* coated probes are similar to that of an uncoated probe. Therefore the quality of water content measurements acquired by high-*K* coated probes is similar to that of an uncoated probe.

[11] Because of the reduced sensitivity, low-*K* coated rods do not measure length-weighted average water contents along their length if the water content varies along their length [*Ferré et al.*, 1996]. On the other hand, like an uncoated probe, high-*K* coated rods measure length-weighted average water contents.

2.2. Dependence on Coating Thickness

[12] The calibration curve (K_{app}-θ relationship) for a low-*K* coated probe increasingly deviates from the curve of an uncoated probe as the coating thickness increases (see K_{coat} = 3 curves in Figure 4). Because of this, variation in the coating thickness from one probe to the next, which can be introduced during the probe coating process, may create inherent error in determining water contents. Furthermore, the coating thickness can be reduced with use due to surface abrasion from multiple insertions into soils. If the calibration relationship (K_{app}-θ) for a probe with its original coating thickness is used when, in fact the probe has some reduced coating thickness, erroneous water contents will be obtained. On the other hand, the K_{app}-θ relationship for high-*K* coated probe (K_{coat} = 35) shows very small difference from the curve of an uncoated probe. This suggests that variations of coating thickness do not introduce significant errors in water content measurements. It may be possible to use one calibration curve for probes with different or variable coating thickness, depending on the required accuracy of water content measurements. When the K_{coat} values are 15 and 100, deviations from the uncoated curve become somewhat larger as shown in Figure 4.

[13] Thus the above analytical evaluation of high-*K* coating clearly shows that (1) high-*K* coating does not reduce the sensitivity of a TDR probe and (2) variations in coating thickness do not introduce significant errors in water content calculations. It also suggests that a dielectric constant of around 35 is the optimal value to be used for high-*K* coating as demonstrated in Figure 4.

3. Epoxy-Ceramic Nanocomposite as High-*K* Coating Material

[14] An epoxy-ceramic nanocomposite was selected as a potential coating because of its high dielectric constant and high adhesion. Brief descriptions of this material and the rod coating method are given below.

[15] Polymer-ceramic composites are of great interest for embedded capacitor manufacturing because they combine the low-temperature processability of polymers and the high dielectric constant of ceramics. Researchers at Georgia Tech have successfully developed a high dielectric composite with high adhesion, thereby eliminating the major constraint to its use for capacitor applications in organic substrates [*Fan et al.*, 2002; *Rao et al.*, 2002].

[16] The composite is produced by mixing a special base matrix and two ceramic fillers (lead magnesium niobate-lead titanate and barium titanate). The special base matrix has a typical dielectric constant of 6, which is much higher than 3 ∼ 4 of an ordinary epoxy matrix. This significantly increases the effective dielectric constant of the composite at a low ceramic loading level [*Fan et al.*, 2002; *Rao et al.*, 2002]. A low ceramic loading (<50% by volume) is important because it increases adhesion of the composite. The base matrix containing 40% of nanosized ceramic filler

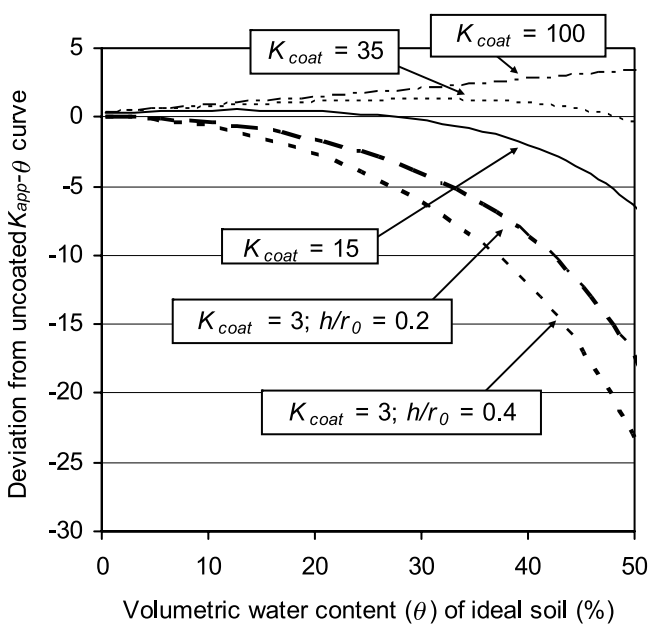

Figure 4. Deviation from uncoated K_{app}-θ curve. The ratio (h/r_0) is 0.4 unless otherwise noted.

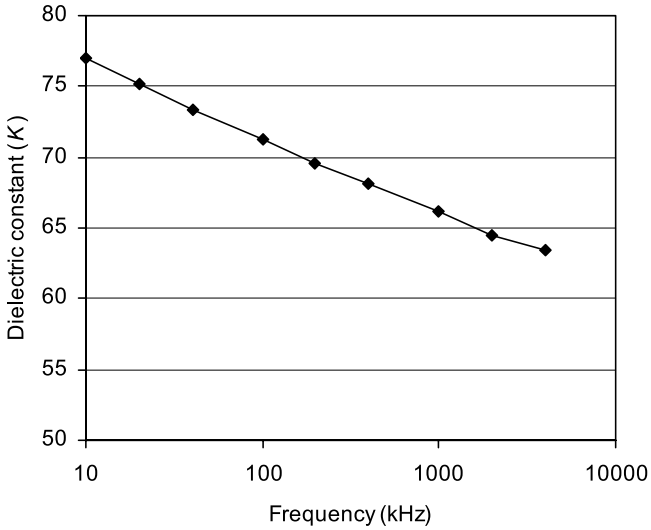

Figure 5. Dielectric constant of epoxy-ceramic nanocomposite.

was ball-milled to obtain the epoxy-ceramic composite. As shown in Figure 5, the dielectric constant of the epoxy-ceramic composite, measured with a HP 4275A LCR meter (refer to *Fan et al.* [2002] for the measurement method), is above 60 at frequencies between 10 kHz and 4 MHz (system measurement limits). It decreases gradually from 77 at 10 kHz to 63 at 4 MHz. The frequency dependent behavior of this material may cause an increase in risetime of the TDR pulse. This can be a potential problem for determining the travel time of the pulse accurately.

[17] Coating of TDR probe rods (stainless steel) was performed as follows. Firstly, the rods are cleaned and dried. Secondly, an epoxy-ceramic composite sample is coated onto the probe rods by briefly immersing the rods into the composite. This was followed by a curing procedure in an oven to harden the coatings. The coating process is repeated a few times to achieve the desired thickness. The first coating was relatively easily performed. However, subsequent coatings to achieve a larger thickness were more difficult to process due to the appearance of small cracks. These cracks were probably caused by stresses induced from temperature changes. They were remedied by locally reapplying the composite using a drawing brush. The maximum average thickness achieved by this procedure was 0.23 mm, which is equivalent to a coating thickness to rod radius ratio (h/r_0) of 0.15.

4. Evaluation of TDR Probe Coated With Epoxy-Ceramic Nanocomposite

[18] Experimental work was carried out to evaluate the performance of TDR probes coated with epoxy-ceramic nanocomposite. This work has two purposes: (1) to evaluate the insulation performance compared to common plastic coatings and (2) to evaluate the effect of high dielectric constant on TDR measurements. The experimental procedure and results are described herein.

4.1. Experimental Procedure

[19] Tap water, NaCl solutions and ethanol were used for the following experiments. Two-rod probes were placed in these liquids and TDR signals were collected using a Tektronix TDR1502C.

4.1.1. TDR Probe

[20] The test setup is schematically shown in Figure 6. Two-rod probes with a bare rod diameter of 3.18 mm and rod spacing of 19 mm were used for the study. Approximately 140 mm of the 150-mm long rod was covered with the coating material. The 10-mm bare length of the rod was necessary for the electrical connection. The probe was constructed so that the rods are easily separated from the body, which electrically connects the lead coaxial cable to the rods. TDR signals were recorded with a probe length of 120 mm immersed in liquid. The starting point of the TDR signal, which is created by the length immersed in liquid, was determined by comparing this signal with a TDR signal independently obtained in air. Superimposing these two signals allows us to determine the separation point, which corresponds to the aforementioned starting point. As demonstrated by several researchers [e.g., *Stein and Kane*, 1983; *Ledieu et al.*, 1986; *Rajkai and Rydén*, 1992; *Kelly et al.*, 1995], a two-rod probe can be used to measure soil dielectric constants without a balun. In this experimental work, a balun was not used for the probe.

4.1.2. Coating Materials

[21] Three coating materials, epoxy-ceramic nanocomposite (EC), polyolefin heat shrink tubing (HS) and enamel spray paint (PA), were used for the study. These materials are electrically insulating and are commonly used for insulation purposes. Heat shrink tubing and paint have been used for insulating TDR probes, although the polymer types are different [*Kelly et al.*, 1995; *Benson and Bosscher*, 1999]. Polyolefin heat shrink tubing and enamel paint should have low K values similar to those of many other plastics. By comparing the experimental results of epoxy-ceramic coating with these two coatings, it is possible to evaluate the performance of the epoxy-ceramic. The coating thickness used for this study is shown in Table 1. A total of 44 measurements for every pair of coated rods was obtained. The thickness of heat shrink coating is greater than the thickness of epoxy-ceramic and paint coating. Heat shrink coating provides the most uniform thickness along the rods.

4.1.3. Evaluation of Insulation Performance

[22] Insulation coating over the rods reduces energy loss due to electrical conduction. To check the insulation performance of the coating materials, coated probes (Table 1) were placed into NaCl solutions with different concentrations (0, 1, 2 and 5 g/L) and TDR signals were collected from the probes. Electrical conductivities of 1, 2, and 5 g/L

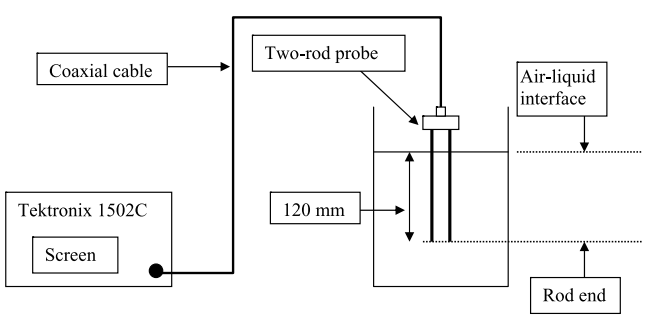

Figure 6. Schematic representation of test setup.

Table 1. Material and Thickness of Coating Applied on Two-Rod Probe

Coating	Thickness (h) Mean (±SD), mm	Thickness to Rod Radius Ratio (h/r_0) Mean (±SD)	Designation
Epoxy-ceramic	0.08 (±0.03)	0.05 (±0.02)	EC-1
Epoxy-ceramic	0.23 (±0.05)	0.15 (±0.03)	EC-2
Enamel paint	0.21 (no data)	0.13 (no data)	PA-2
Enamel paint	0.25 (±0.04)	0.16 (±0.02)	PA-3
Heat shrink	0.29 (±0.01)	0.18 (±0.01)	HS-1
Heat shrink	0.59 (±0.01)	0.37 (±0.01)	HS-2

solutions are 1.8, 3.5, and 8.4 dS/m, respectively, according to *Wolf* [1966]. By examining the magnitude of rod-end reflections in these signals, the effectiveness of insulation coatings are evaluated.

4.1.4. Effect of High Dielectric Coating

[23] As shown in Figures 2–4, apparent soil dielectric constants measured with a high-K coated probe (i.e., epoxy-ceramic coated probe) and an uncoated probe are similar. To investigate this feature, the dielectric constants of three types of liquids were measured using coated rods. Tap water, ethanol-water mixture (2:1) and ethanol were used for these tests. The K values of these liquids measured using an uncoated probe were about 82, 40, and 23, respectively.

4.2. Experimental Results and Discussion

4.2.1. Result and Discussion of Evaluation of Insulation Performance

[24] Insulation performance of epoxy-ceramic coating was investigated by comparing with those of paint and heat shrink coatings using NaCl solutions of different concentrations.

[25] Figures 7–9 show the waveforms collected from TDR probes using a TDR1502C. All coated probes showed greater end reflections than uncoated probes. Epoxy-ceramic coated probes showed greater end reflection than the uncoated probe (Figure 7). For example, the magnitude of end reflection from EC-2 in 1 g/L solution is about 1.5 times greater than that from the uncoated probe in the same solution. However, the improvement was moderate compared to other coated probes (Figures 8 and 9). As shown in Figure 7, the end reflections from EC probes in 2 g/L solution are very small. In a 5 g/L solution, the end reflections are negligible, so no graph is shown for this case. On the other hand, PA and HS coated probes showed clearer end reflections in 2 g/L solution. For example, the magnitudes of end reflections from PA-2 and HS-1 in 2 g/L solution are more than two times greater than that from EC-2 in the same solution. A common trend with all coated probes is that the end reflection improves as the coating thickness increases.

[26] The end reflection from EC-2 is smaller than those of PA-2 and PA-3 although the coating thickness is similar. The reason for this is unknown. However, the end reflection should improve by increasing the coating thickness as suggested in Figure 7. In this study, because of the cracking of epoxy-ceramic coating, the maximum achievable coating thickness was limited to 0.23 mm as shown in Table 1. If a thicker coating becomes possible by improving the composite material and the coating technique, the insulation performance should improve.

4.2.2. Result and Discussion of Effect of High Dielectric Coating

[27] The apparent dielectric constants of three types of liquids were measured using the coated two-rod probes. Table 2 shows the apparent dielectric constants measured using EC-2, PA-3 and HS-1. The coating thicknesses of these probes are similar. Therefore the results of the dielectric measurements can be compared.

[28] The dielectric constants of the ethanol-water mixture and ethanol obtained from uncoated and epoxy-ceramic coated probes were very similar. This means that the epoxy-ceramic coating has almost no influence on the measured apparent dielectric constant. As discussed previously, this is due to the high K value of the epoxy-ceramic coating. On the other hand, paint and heat shrink coating significantly reduced the apparent K values. Thus the test

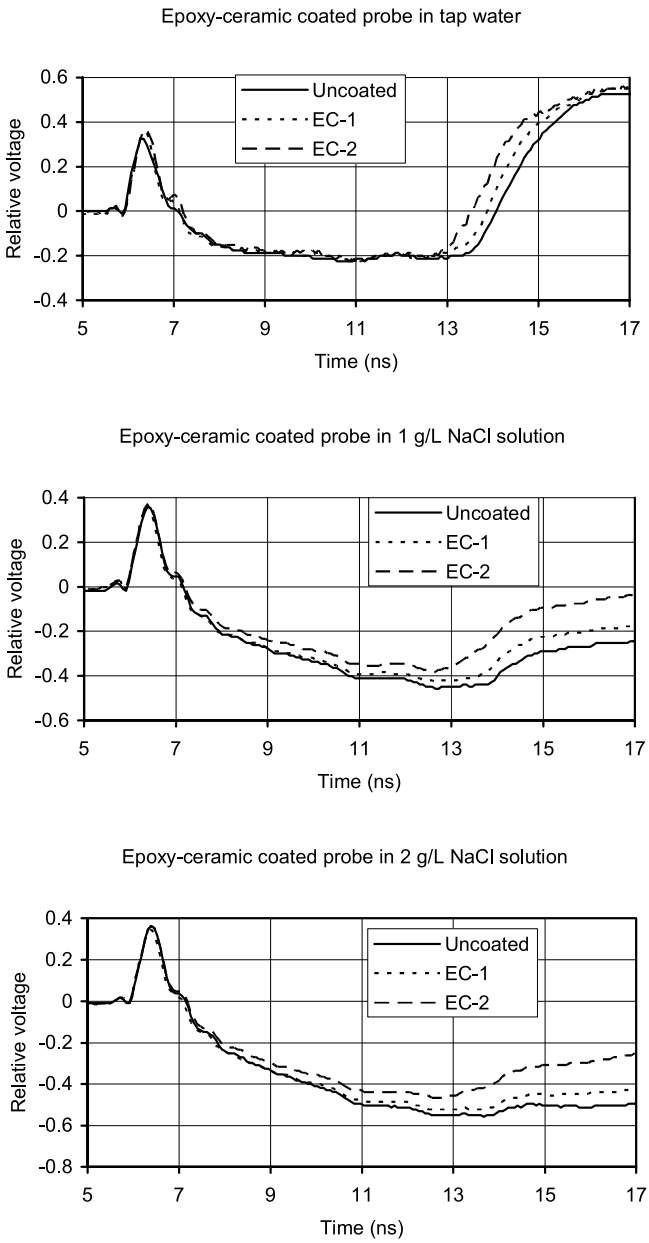

Figure 7. Response of epoxy-ceramic coated probe in NaCl solutions.

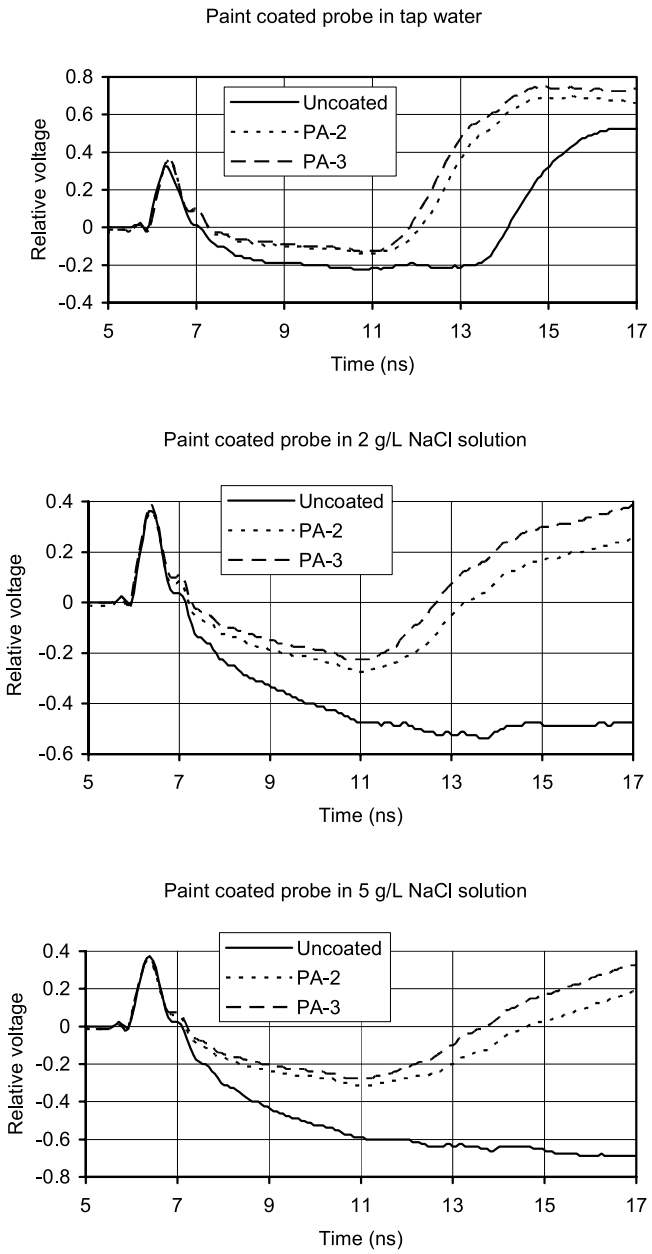

Figure 8. Response of paint coated probe in NaCl solutions.

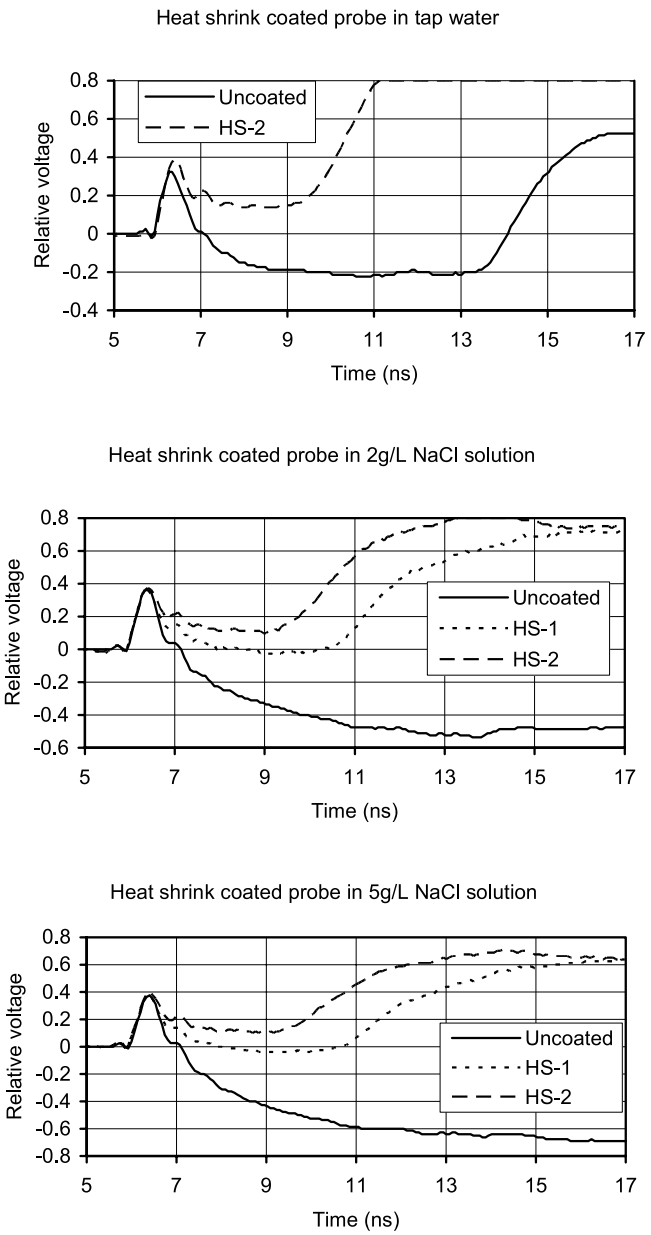

Figure 9. Response of heat shrink coated probe in NaCl solutions.

results demonstrated the useful feature of high-K coating reasonably well.

[29] Using the data in Tables 1 and 2, it is possible to estimate dielectric constants of the coating materials. By substituting the values in Tables 1 and 2 into equation (3), the K_{coat} values were estimated. Both upper and lower values (mean ± SD) shown in Table 1 were used. The results of the probes tested in water and ethanol-water mixture (Table 2) were used for the calculations. Because the dielectric constant estimates from EC-2 in ethanol was too sensitive to a small variation of K_{app} (= 23.4) in Table 2, it was impossible to give a valid estimation.

[30] The estimated dielectric constants are listed in Table 3. The estimated K value of the epoxy-ceramic coating was around 20. This is quite low compared to the K values measured up to 4 MHz frequency (Figure 5). The TDR instrument (TDR1502C) uses a step pulse that contains frequencies from 20 kHz to 1.5 GHz [*Heimovaara*, 1994]. The dielectric constant of the epoxy-ceramic appears to be lower than expected at these higher frequencies. To maximize the usefulness of high dielectric coating, the K_{coat} value should be close to the high end of K values ($30 \sim 40$) exhibited by many types of soils. In addition, the

Table 2. Summary of Apparent Dielectric Constants (K_{app}) Measured Using the Uncoated and Coated Two-Rod Probes

Liquids	Uncoated	EC-2	PA-3	HS-1
Water	82.5	73.1	47.1	28.0
Ethanol-Water (2:1)	39.7	37.6	31.4	19.2
Ethanol	22.6	23.4	17.6	14.0

Table 3. Estimated Dielectric Constants of Coating Materials

Material	Epoxy-Ceramic	Enamel Paint	Heat Shrink
Estimated K (water)	21–28	5–7	3
Estimated K (ethanol-water mixture)	18–21	6–8	2

K value should be stable in the frequency ranges used by TDR instruments to minimize an increase in risetime. Further improvement of epoxy-ceramic coating, including an investigation on high frequency performance, is necessary to achieve better probe performance. The K values of paint and heat shrink coatings are also shown in Table 3. The values are similar to the K values of common polymers.

5. Conclusions and Future Work

[31] Advantages of high dielectric insulation for TDR sensors were analytically examined. It is demonstrated that a coating with a dielectric constant of around 35 has a small influence on the measured apparent dielectric constant. This indicates that (1) high-K coating does not reduce the sensitivity of a TDR probe and (2) variations in coating thickness do not introduce significant errors in water content calculations, as opposed to low-K coating. It may be possible to use one calibration curve (K_{app}-θ relationship) for high K-coated probes with different thicknesses, depending on the accuracy requirement of water content measurements.

[32] An epoxy-ceramic nanocomposite was selected as a high-K coating material because of its high dielectric constant and adhesive property. Using two-rod probes coated with this composite, the insulation performance was experimentally evaluated. The epoxy-ceramic coated probes showed greater end reflections than those of an uncoated probe in saline solutions. However, the reflections were weaker compared to those of probes with plastic coatings. Better insulation performance of the epoxy-ceramic composite should be obtained by increasing the coating thickness.

[33] The dielectric constants of liquids (tap water, ethanol-water mixture and ethanol) obtained from epoxy-ceramic coated probes were similar to those from uncoated probes. This means that the epoxy-ceramic coating has a negligible influence on the measured apparent dielectric constant. Thus the test results demonstrated the useful feature of high-K coating reasonably well. An estimated dielectric constant of the epoxy-ceramic composite for the broadband frequencies of the TDR instrument (TDR1502C) was about 20, which is lower than the K values measured up to 4 MHz frequency. High frequency performance needs to be investigated to improve the composite.

[34] The results of the analytical and experimental work provide the framework for designing an improved high-K insulation material. Firstly, the type of ceramics and the ceramic loading level should be properly selected so that the dielectric constant of the insulation material will be around 35 at a frequency range of 20 kHz to 1.5 GHz. Secondly, the ceramic loading level must be as low as possible to improve the adhesion and durability of the insulation material. Selection of an epoxy material, which has a low possibility of cracking during curing, may also be important since the appearance of cracks during curing limited the coating thickness. This helps to create a thicker coating with a better insulation performance.

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References

Annan, A. P. (1977), Time-domain reflectometry—Air-gap problem for parallel wire transmission lines, in *Report of Activities, Part B, Rep. 77-1B*, pp. 59–62, Geol. Surv. Of Can., Ottawa, Ontario.

Baran, E. (1994), Use of time domain reflectometry for monitoring moisture changes in crushed rock pavements, in *Proceedings of Symposium and Workshop on Time Domain Reflectometry in Environmental, Infrastructure, and Mining Applications*, *Spec. Publ. SP 19-94*, pp. 349–356, U.S. Bur. of Mines, Washington, D. C.

Benson, C. H., and P. J. Bosscher (1999), Time-domain reflectometry (TDR) in geotechnics: A review, *Nondestructive and Automated Testing for Soil and Rock Properties*, *ASTM STP 1350*, edited by W. A. Marr and C. E. Fairhurst, Am. Soc. for Test. and Mater., West Conshohocken, Pa.

Fan, L., Y. Rao, C. Tison, K. S. Moon, S. V. Pothukuchi, and C. P. Wong (2002), Use of dispersant in high K polymer-ceramic nano-composite to improve manufacturability and performance of integral capacitors, paper presented at the 52nd Electronic Components and Technology Conference, Inst. of Electr. and Electron. Eng., San Diego, Calif., 28–31 May.

Ferré, P. A., D. L. Rudolph, and R. G. Kachanoski (1996), Spatial averaging of water content by time domain reflectometry: Implications for twin rod probes with and without dielectric coating, *Water Resour. Res.*, *32*, 271–279.

Heimovaara, T. J. (1994), Frequency domain analysis of time domain reflectometry waveforms: 1. Measurement of the complex dielectric constant of soils, *Water Resour. Res.*, *30*, 189–199.

Jones, S. B., and D. Or (2001), Frequency-domain methods for extending TDR measurement range in saline soils, paper presented at the Second International Symposium and Workshop on Time Domain Reflectometry for Innovative Geotechnical Applications, Infrastructure Technol. Inst., Northwestern Univ., Evanston, Ill., 5–7 Sept.

Kelly, S. F., J. S. Selker, and J. L. Green (1995), Using short soil moisture probes with high-bandwidth time domain reflectometry instruments, *Soil Sci. Soc. Am. J.*, *59*, 97–102.

Ledieu, J., P. De Ridder, P. De Clerck, and S. Dautrebande (1986), A method of measuring soil moisture by time-domain reflectometry, *J. Hydrol.*, *88*, 319–328.

Lide, D. R. (Ed.) (1995), *CRC Handbook of Chemistry and Physics*, 76th ed., CRC Press, Boca Raton, Fla.

O'Connor, K. M., and C. H. Dowding (1999), *Geomeasurements by Pulsing TDR Cables and Probes*, CRC Press, Boca Raton, Fla.

Rajkai, K., and B. E. Rydén (1992), Measuring areal soil moisture distribution with the TDR method, *Geoderma*, *52*, 73–85.

Rao, Y., S. Ogitani, P. Kohl, and C. P. Wong (2002), Novel polymer-ceramic nanocomposite based on high dielectric constant epoxy formula for embedded capacitor application, *J. Appl. Polymer Sci.*, *83*, 1084–1090.

Stein, J., and D. L. Kane (1983), Monitoring the unfrozen water content of soil and snow using time domain reflectometry, *Water Resour. Res.*, *19*, 1573–1584.

Topp, G. C., J. L. Davis, and A. P. Annan (1980), Electromagnetic determination of soil water content: Measurement in coaxial transmission lines, *Water Resour. Res.*, *16*, 574–582.

Wolf, A. V. (1966), *Aqueous Solutions and Body Fluids. Their Concentrative Properties and Conversion Tables*, Hocher Medical Div., Harper-Collins, New York.

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